Chapter 2
Operational Theory of NAVSTAR GPS

This chapter provides a general overview of the basic operating principles and theory of the NAVSTAR GPS. The references listed in Appendix A should be used for more detailed background of all the topics covered in this chapter.

2-1. Global Positioning System (GPS)

The NAVSTAR GPS is a passive, satellite-based, navigation system operated and maintained by the Department of Defense (DoD). Its primary mission is to provide passive global positioning/navigation for land-, air-, and sea-based strategic and tactical forces. A GPS receiver is simply a range measurement device; distances are measured between the receiver antenna and the satellites, and the position is determined from the intersections of the range vectors. These distances are determined by a GPS receiver which precisely measures the time it takes a signal to travel from the satellite to the station. This measurement process is similar to that used in conventional pulsing marine navigation systems and in phase comparison electronic distance measurement (EDM) land surveying equipment.

a. GPS operating and tracking modes. There are basically two general operating modes from which GPS-derived positions can be obtained: absolute positioning and relative or differential positioning. Within each of these two modes, range measurements to the satellites can be performed by tracking either the phase of the satellite's carrier signal or the pseudo-random noise codes modulated on the carrier signal. In addition, GPS positioning can be performed with the receiver operating in a static or dynamic (kinematic) environment. This variety of operational options results in a wide range of accuracy levels which may be obtained from the NAVSTAR GPS. Accuracies can range from 100 m down to the sub-centimeter level, as shown in Figure 2-1. Increased accuracies to the sub-centimeter level require additional observing time and, until recently, could not be achieved in real time. Selection of a particular GPS operating and tracking mode (i.e., absolute, differential, code, carrier, static, kinematic, or combinations thereof) depends on the user application. USACE survey applications typically require differential positioning using carrier phase tracking. Some dredge control and hydrographic applications can use differential code measurements. Absolute modes are rarely used for geodetic surveying applications except when worldwide reference control is being established.

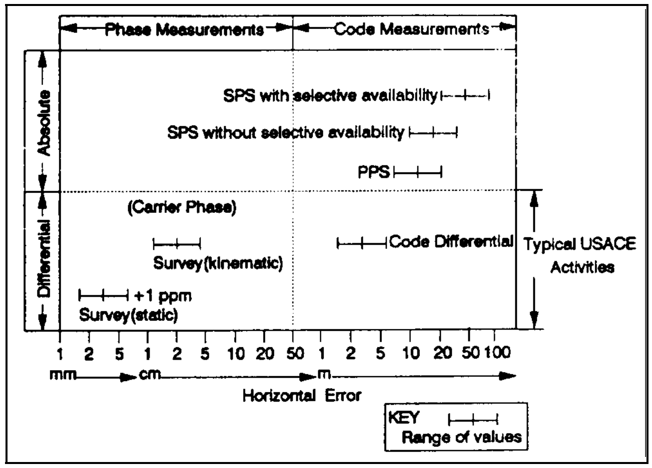

Figure 2-1. GPS operating modes and accuracies

b. Absolute positioning. The most common military and civil (i.e., commercial) application of GPS is "absolute positioning" for real-time navigation. When operating in this passive, real-time navigation mode, ranges to NAVSTAR satellites are observed by a single receiver positioned on a point for which a position is desired. This receiver may be positioned to be stationary over a point (i.e., static, Figure 2-2) or in motion (i.e., kinematic positioning, such as on a vehicle, aircraft, missile, or backpack). Two levels of absolute positioning accuracy may be obtained from the NAVSTAR GPS. These are called the (1) Standard Positioning Service (SPS) and (2) Precise Positioning Service (PPS).

(1) Using the SPS, the user is able to achieve real-time 3D absolute point positioning on the order of 100 m. The SPS is the GPS signal that the DoD authorizes to civil users. This level of accuracy, achievable by the civil user, is due to the deliberate degradation of the GPS signal by the DoD for national security reasons. DoD degradation of the GPS signal is referred to as "Selective Availability" or S/A. DoD has also implemented Anti-Spoofing or A-S which will deny the SPS user the more accurate P-code. S/A and A-S will be discussed further in Chapter 5.

(2) Use of the PPS requires authorization by DoD to have a decryption device capable of deciphering the encrypted GPS signals. USACE is an authorized user; however, actual use of the equipment has security implications. Real-time 3D absolute positional accuracies of 16-20 m are attainable through use of the PPS.

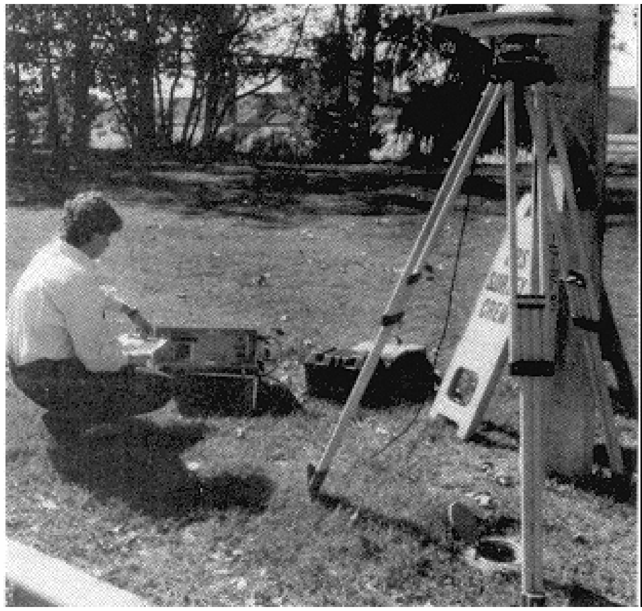

Figure 2-2. Performing static differential GPS surveys

(3) With certain specialized GPS receiving equipment, data processing refinements, and long-term static observations, absolute positional coordinates may be determined to accuracy levels less than a meter. Applications of this are usually limited to worldwide geodetic reference surveys.

(4) These absolute point positioning accuracy levels are not suitable for USACE surveying applications other than rough reconnaissance work or general vessel navigation. They may be useful for some military topographic surveying applications (e.g., artillery surveying).

c. Differential or relative GPS positioning. Differential positioning is simply a process of measuring the differences in coordinates between two receiver points, each of which is simultaneously observing/measuring satellite code ranges and/or carrier phases from the NAVSTAR GPS constellation. The process actually involves the measurement of the difference in ranges between the satellites and two or more ground observing points. The range measurement is performed by a phase difference comparison, using either the carrier phase or code phase. The basic principle is that the absolute positioning errors at the two receiver points will be approximately the same for a given instant. The resultant accuracy of these coordinate differences is at the meter level for code phase observations and at the centimeter level for carrier phase tracking. These coordinate differences are usually expressed as 3D "baseline vectors," which are comparable to conventional survey azimuth/distance measurements. Differential GPS (DGPS) positioning can be performed in either a static or kinematic mode. Further information on DGPS can be found in Chapter 6.

2-2. NAVSTAR Program Background

A direct product of the "space race" of the 1960's, the NAVSTAR GPS is actually the result of the merging of two independent programs that were begun in the early 1960's: the U.S. Navy's TIMATION Program and the U.S. Air Force's 621B Project. Another system similar in basic concept to the current NAVSTAR GPS was the U.S. Navy's TRANSIT program, which was also developed in the 1960's. Currently, the entire system is maintained by the NAVSTAR GPS Joint Program Office (JPO), a North Atlantic Treaty Organization (NATO) multiservice type organization. DoD originally designed the NAVSTAR GPS to provide sea, air, and ground forces of the United States and members of NATO with a unified, high-precision, all-weather, worldwide, real-time positioning system. Mandated by Congress, GPS is freely used by both the military and civilian public for real-time absolute positioning of ships, aircraft, and land vehicles, as well as highly precise differential point positioning.

2-3. NAVSTAR System Configuration

The NAVSTAR GPS consists of three distinct segments: the space segment (satellites), the control segment (ground tracking and monitoring stations), and the user segment (air-, land-, and sea-based receivers). See Figure 2-3 for a representation of the basic GPS system segments.

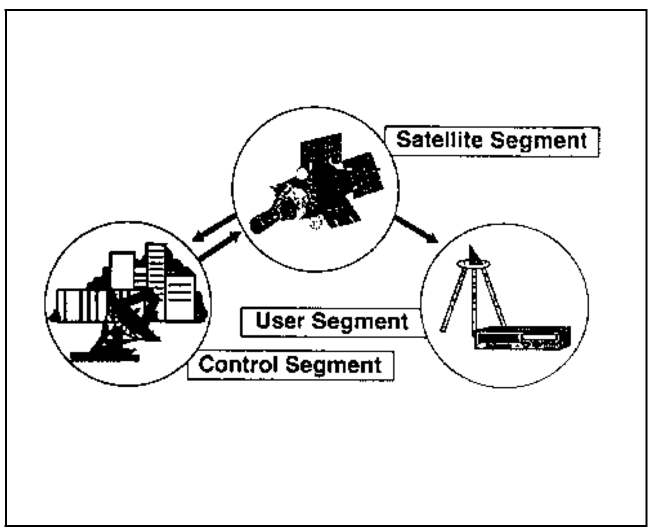

Figure 2-3. GPS system segments

a. Space segment. The space segment consists of all GPS satellites in orbit. The first generation of satellites was the Block I or developmental. Several of these are still operational. A full constellation of Block II or production satellites is presently being put into orbit using Delta II launch vehicles. *The full 24-satellite constellation is scheduled to be in orbit by early FY94.* When this full constellation is implemented, there will be 24 Block II operational satellites (21 primary with 3 active on-orbit spares). There will be four satellites in each of six orbital planes inclined at 55 deg to the equator. The satellites will be at altitudes of 10,898 nm (20,183 km), and have 11-hr-56-minute orbital periods. The three active spares will be transparent to the user on the ground; i.e., the user will not be able to tell which are operational satellites and which are spares. A procurement action for Block IIR (R is for replacement) satellites is underway, thus ensuring full system performance through the year 2025. Figure 2-4 illustrates some of the common design characteristics of the NAVSTAR GPS fully configured Block IIR constellation.

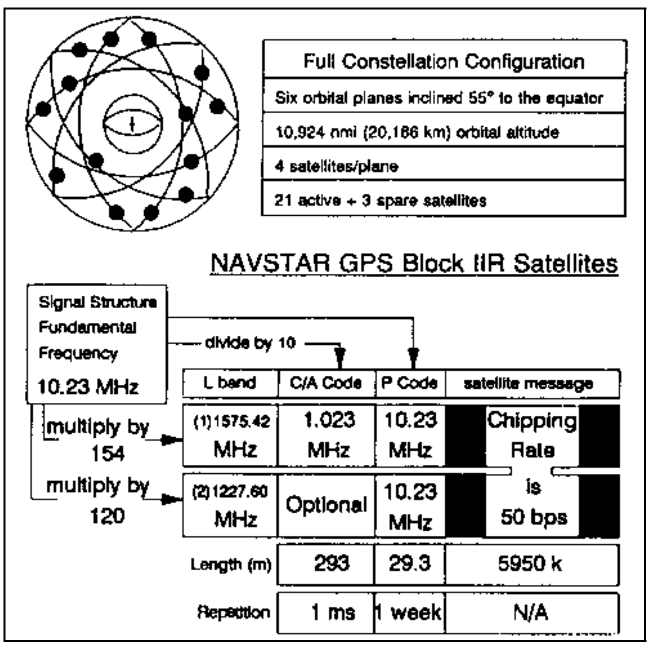

Figure 2-4. NAVSTAR GPS Block IIR constellation

b. Control segment. The GPS control segment consists of five tracking stations located throughout the world (Figure 2-5). These stations are in Hawaii, Colorado, Ascension Island, Diego Garcia, and Kwajalein. The information obtained from tracking the satellites is used in controlling the satellites and predicting their orbits. Three of the stations (Ascension, Diego Garcia, and Kwajalein) are used for transmitting information back to the satellites. The Master Control Station is located at Colorado Springs, Colorado. All data from the tracking stations are transmitted to the Master Control Station where they are processed and analyzed. Ephemerides, clock corrections, and other message data are then transmitted back to the three stations for subsequent transmittal back to the satellites. The Master Control Station is also responsible for the daily management and control of the GPS satellites and the overall control segment.

c. User segment. The user segment represents the ground-based receiver units that process the NAVSTAR satellite signals and arrive at a position of the user. It consists of both military and civil activities for an almost unlimited number of applications in a variety of air-, sea-, or land-based platforms. Land surveying applications (including those of USACE) represent a small percentage of current and potential GPS users.

2-4. GPS Broadcast Frequencies and Codes

Each NAVSTAR satellite transmits signals on two L-band frequencies, designated as L1 and L2. The L1 carrier frequency is 1575.42 megahertz (MHz) and has a wavelength of approximately 19 centimeters (cm). The L2 carrier frequency is 1227.60 MHz and has a wavelength of approximately 24 cm. The L1 signal is modulated with a Precise Code (P-code) and a Coarse Acquisition Code (C/A-code). The L2 signal is modulated with only the P-code. Each satellite carries precise atomic clocks to generate the timing information needed for precise positioning. A navigation message is also transmitted on both frequencies. This message contains ephemerides, clock correction and coefficients, health and status of satellites, almanacs of all GPS satellites, and other general information.

a. Pseudo-random noise. The modulated C/A- and P-codes are referred to as pseudo-random noise (PRN). This pseudo-random code is actually a sequence of very precise time marks that permit the ground receivers to compare and compute the time of transmission between the satellite and ground station. From this transmission time, the range to the satellite can be derived. This is the basis behind GPS range measurements. The C/A-code pulse intervals are approximately every 300 m in range and the more accurate P-code every 30 m.

b. Pseudo-ranges. A pseudo-range is the time delay between the satellite clock and the receiver clock, as determined from C/A- or P-code pulses. This time

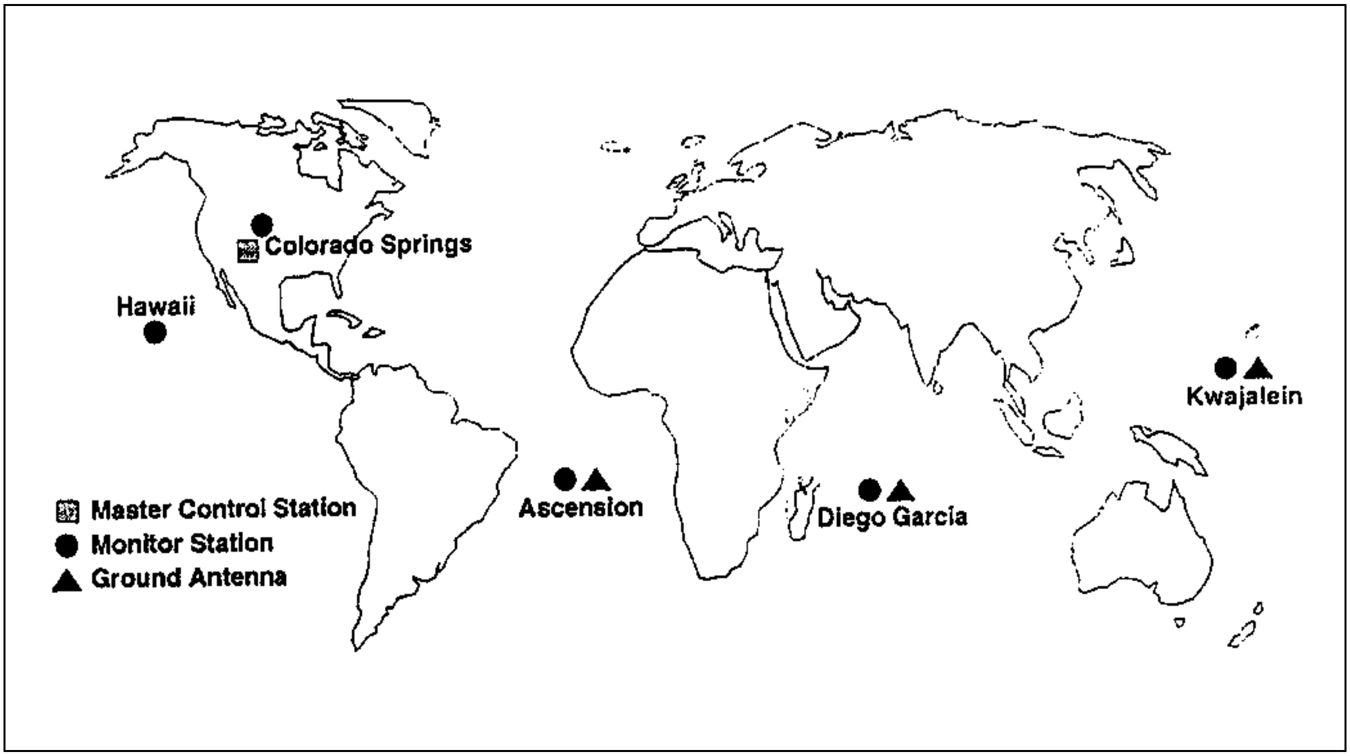

Figure 2-5. GPS control station network

difference equates to the range measurement but is called a pseudo-range since at the time of the measurement, the receiver clock is not synchronized to the satellite clock. In most cases, an absolute 3D real-time navigation position can be obtained by observing at least four simultaneous pseudo-ranges.

c. SPS. The SPS uses the less precise C/A-code pseudo-ranges for real-time GPS navigation. Due to deliberate DoD degradation of the C/A-code accuracy, 100 m in horizontal and 156 m in vertical accuracy levels result. These accuracy levels are adequate for most civil or nonmilitary applications, where only approximate real-time navigation is required.

d. PPS. The PPS is the fundamental military real-time navigation use of GPS. Pseudo-ranges are obtained using the higher pulse rate (i.e., higher accuracy) P-code on both frequencies (L1 and L2). Real-time 3D accuracies at the 16-m level (and 10 m horizontal) can be achieved with the PPS. The P-code is encrypted to prevent unauthorized civil or foreign use. This encryption will require a special key to obtain this 16-m accuracy. These accuracies are adequate for some USACE surveying and mapping projects (i.e. GIS database input).

e. Carrier phase measurements. Carrier frequency tracking measures the phase differences between the Doppler shifted satellite and receiver frequencies. The phase differences are continuously changing due to the changing satellite earth geometry. However, such effects are resolved in the receiver and subsequent data post-processing. When carrier phase measurements are observed and compared between two stations (i.e., relative or differential mode), baseline vector accuracy between the stations below the centimeter level is attainable in three dimensions. New receiver technology and processing techniques have allowed for carrier phase measurements to be used in real-time centimeter positioning.

2-5. GPS Broadcast Messages and Ephemeris Data

Each NAVSTAR GPS satellite periodically broadcasts data concerning clock corrections, system/satellite status, and most critically, its position or ephemeris data. There are two basic types of ephemeris data: broadcast and precise.

a. Broadcast ephemerides. The broadcast ephemerides are actually predicted satellite positions broadcast within the navigation message that are transmitted from the satellites in real time. The ephemerides can be acquired in real time by a receiver capable of acquiring either the C/A- or P-code. The broadcast ephemerides are computed using past tracking data of the satellites. The satellites are tracked continuously by the monitor stations to obtain more recent data to be used for the orbit predictions. The data are analyzed by the Master Control Station, and new parameters for the satellite orbits are transmitted back to the satellites. This upload is performed daily with new predicted orbital elements transmitted every hour by the navigation message.

b. *Precise ephemerides.* The precise ephemerides are based on actual tracking data that are post-processed to obtain the more accurate satellite positions. These ephemerides are available at a later date and are more accurate than the broadcast ephemerides because they are based on actual tracking data and not predicted data. Nonmilitary users can obtain this information from the National Geodetic Survey (NGS) or from private sources that maintain their own tracking networks and provide information for a fee. For most USACE survey applications, the broadcast ephemerides are adequate to obtain the needed accuracies.

c. See Appendix D for sources of GPS information and its status.